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Will E. Leland, Daniel V. Wilson
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Abstract: The interconnection of local area networks is increasingly important, but little data are available on the characteristics of the aggregate traffic that LANs will be submitting to the interconnection media. In order to understand the interactions between LANs and the proposed interconnection networks (MANs, WANs, and BISDN networks), it is necessary to study the behavior of this external LAN traffic over many time scales -- from milliseconds to hundreds of seconds. We present a high... [\(Update\)](#)

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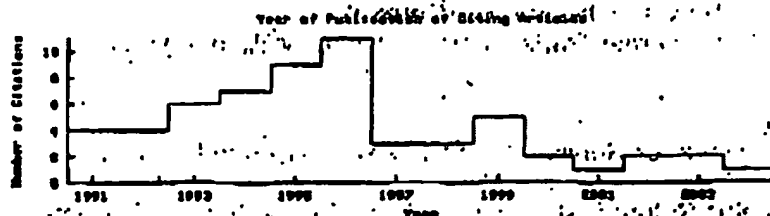
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High Time-Resolution Measurement and Analysis of LAN Traffic: Implications for LAN Interconnection

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Abstract

The interconnection of local area networks is increasingly important, but little data are available on the characteristics of the aggregate traffic that LANs will be submitting to the interconnection media. In order to understand the interactions between LANs and the proposed interconnection networks (MANs, WANs, and BISDN networks), it is necessary to study the behavior of this external LAN traffic over many time scales - from milliseconds to hundreds of seconds. We present a high time-resolution hardware monitor for Ethernet LANs that avoids the shortcomings of previous monitoring tools, such as traffic burst clipping and timestamp jitter. Using data recorded by our monitor for several hundred million Ethernet packets, we present an overview of the short-range time correlations in external LAN traffic. Our analysis shows that LAN traffic is extremely bursty across time domains spanning six orders of magnitude. We compare this behavior with simple formal traffic models and employ the data in a trace-driven simulation of the LAN-BISDN interface proposed for the SMDSSM service. Our results suggest that the pronounced short-term traffic correlations, together with the extensive time regime of traffic burstiness, strongly influence the patterns of loss and delay induced by LAN interconnection.

1. Introduction

As the interconnection of local area networks becomes increasingly important, understanding the interactions between LAN traffic and larger area (MAN, WAN, and BISDN) networks becomes ever more critical. Because the detailed behavior of LAN traffic greatly influences both the performance and the design of potential LAN interconnection schemes, we need to understand and realistically model LAN traffic over a very wide range of time scales: from milliseconds to days. Unfortunately, existing tools for measuring LAN traffic cannot accurately resolve short time scales, and existing approaches to analyzing LAN traffic do not provide adequate information over such disparate time domains. In this paper, we describe a novel hardware monitor for Ethernet[®] traffic, characterize its accuracy, and present some analysis perspectives for understanding and characterizing the resulting traffic measurements. We then illustrate the importance of realistic traffic characterization with an example drawn from a simulation study of the packet loss and delay effects induced by one LAN-to-BISDN access proposal.

Although there have been many studies of LAN traffic since the early Ethernet measurements of Shoch and Hupp,^[1] the emphasis has been on intermediate time scale behavior^{[2] [3] [4]} or on user-oriented measures of behavior such as LAN throughput and delay^{[5] [6]}. More recently for our study, little published data are available on the packet loss and timestamp errors introduced by the data collection techniques employed. The early studies typically used time measurements with low resolution (on the order of one second), with high loss rates (as much as 5% to 9% of all packets). Recent studies, such as Feldmiller^[7], Grunella^[8], and Jain and Routhier^[9], have made higher time-resolution measurements, but have relied on operating system modifications to handle timestamping, with a resulting loss of timing accuracy and clipping of traffic peaks: the systems reported still lose between 1% and 5% of

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the LAN packets. Many of these studies, moreover, have employed experimental configurations that actively generated traffic on the network being monitored. These constraints are less significant for the purposes of their studies; however, in order to accurately characterize bursty aggregate LAN traffic, our study required that rapid sequences of packets be completely captured and that arrival timestamps have known and tightly bounded errors.

Previous studies of LAN traffic have two other restrictions that make them less well suited for understanding the effects of LAN interconnection: they have generally considered all *internal* packet traffic (that is, all packets on a local network, regardless of ultimate source or destination), and they have often used extremely small sample periods - often only a few hundreds of thousands of packets collected within a short time span. Our emphasis in this study is on the aggregate traffic that a LAN might offer to a WAN providing LAN interconnection services; for this reason, we were obliged to examine not only the low-level addresses of packets, but the higher-level protocol source and destination fields, in order to distinguish purely local traffic from *external* traffic (that is, packets originating on one LAN but ultimately destined for delivery on some other LAN). LAN traffic is, of course, highly variable over all time scales, so distinguishing temporary aberrations from normal behavior can be difficult when only small, closely spaced sample periods are studied. By collecting detailed records on hundreds of millions of packets, on different intra-company networks, over the course of a year, this study can concentrate on features of the observed traffic that persist across time, and can illuminate some of the patterns of variation.

Our paper first describes our hardware Ethernet monitor, with its design, testing, and performance. Section 3 describes some analysis techniques we have found appropriate for understanding data traffic across these time domains, with illustrations drawn from our analysis of the extensive Ethernet traffic measurements provided by our monitor. Section 4 then explores the loss and delay effects of one proposed BISDN service for interconnecting LANs, contrasting the results derived from external traffic data with those derived from simple formal models. Section 5 briefly summarizes our results.

2. LAN Traffic Monitoring

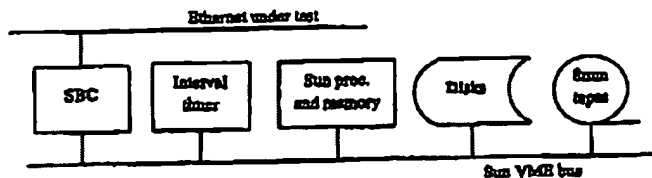
2.1 Approaches to LAN monitoring

There are two major approaches to monitoring LANs: *on-the-fly* and *retrospective* analysis. In the first approach, the monitor looks at each packet as it comes in and takes some action determined by the contents of the packet. Monitors taking the second approach record some portion of every packet on the network for later analysis, without performing realtime data reduction. Most commercial LAN analyzers fall somewhere between these two extremes, but have severe limitations on how many packets they can capture and on how fast the captured packets are spooled to disk, making them unsuitable for gathering data for long-term studies. Our monitor attempts to combine the exhaustive data analysis potential of retrospective techniques with sufficient throughput capacity to entirely eliminate peak clipping. Our monitor records a timestamp, length, status, and 60 bytes of packet data for every packet seen on the network under examination.

2.2 Design of the monitor

The monitor hardware consists of three major parts: a dedicated 20 MHz MC68030-based single board computer with onboard LANCE Ethernet interface, a Sun-3 workstation with local hard disk drives, and a pair of 2.3 gigabyte capacity 8mm helical scan digital tape drives. The single board computer (SBC) and tape drives are interfaced to the VME bus of the Sun workstation along with an interval timer board. Figure 2.2.1 shows the structure of the monitor.

Figure 2.2.1: Block Diagram of Monitor



The SBC forms the heart of the monitor. Its on-board Ethernet interface is connected to the network to be studied. The SBC executes a highly optimized program that timestamps each packet as it comes in, places the first 60 bytes

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of the packet in a buffer, and records the status of the Ethernet interface. When a buffer is filled, the SBC signals a high-priority Unix process running on the Sun workstation which then copies the buffer to a disk file. A lower-priority Unix process then spools the data to 8mm tape. Each stage of our monitor provides buffering for the next, lower bandwidth one - the RAM on the SBC buffers data bound for the lower bandwidth disk, and the disk buffers data bound for the even lower bandwidth 8mm tape drive. By using the SBC, we are able to dedicate a high performance processor to servicing the Ethernet interface chip, thus eliminating much of the timestamp jitter inherent in other monitor designs. We are able to ensure that all packets are recorded by using both a dedicated processor and extensive hierarchical buffering.

A typical day-long trace from a fairly heavily loaded network (roughly 20% average utilization averaged over a day's time) yields 2 gigabytes of trace data, filling one 8mm tape. We routinely make traces a week in length of over 100 million packets with no loss of data.

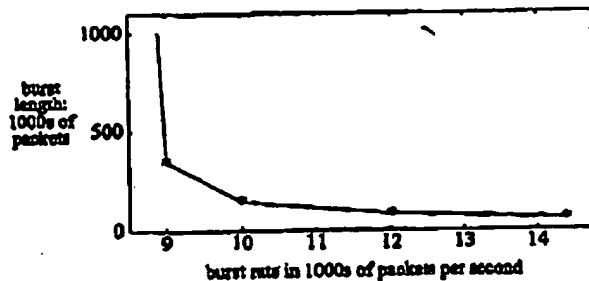
2.3 Measuring the Measurer

In designing a monitor for recording LAN packets, one hopes to design a system that can capture every packet at any network load and timestamp them accurately. Our system does not handle every load that is possible on an Ethernet network, but does handle loads far in excess of any we have yet observed in actual traffic. This section of the paper will briefly characterize the behavior of the monitor under pathological network loads.

There are three mechanisms by which the system can fail to record packets: the Ethernet interface chip on the SBC may not be able to get to memory sufficiently quickly to store a packet; the monitor program on the SBC may not be able to supply buffers to the LANCE fast enough even though buffers are available; and there may be no buffers available to give to the LANCE.

We tested the system by using a load generator to supply a periodic stream of 64-byte packets. The packets bore sequence numbers, allowing us to precisely determine which packets were lost and when. We have found that the most useful way to characterize the loss behavior of the monitor is to consider the length of bursts that can be recorded without error. At the highest possible Ethernet rate of 14,400 packets per second, the first 56,000 packets of a burst are captured without loss. From Figure 2.3.1, we see that as the packet rate is lowered, the burst length that can be captured without loss grows. The ultimate limitation to the very long term packet rate that can be captured is the bandwidth of the 8mm digital tapes. In the current implementation, about 2,500 packets per second may be captured without loss for as long as blank tapes are provided.

Figure 2.3.1: Burst lengths recorded without loss



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We also examined the accuracy of the timestamps. We tested the system with 64-byte packets precisely generated at 1 millisecond intervals. Analysis of the resulting monitor measurements shows that the timestamps are quite accurate - within 10 microseconds - until the Unix system copies a block of data to the disk. While the block is being copied, the stamps are only accurate to about 50 microseconds. At 1000 packets per second, about 14% of the packets are received while buffers are being moved to the disk. At higher packet rates, many more of the timestamps are affected when moving the data to disk. When tested against an artificial stream of 8,000 packets per second, the timestamps are still accurate to within 100 microseconds: roughly two orders of magnitude better than other long-term studies.

It is worth noting that the packet rates we are using to test the system are far in excess of that observed on any of the networks we monitored. The greatest number of packets in any second of actual traffic was 1862, much lower than any of the pathological rates used in stress testing the system.

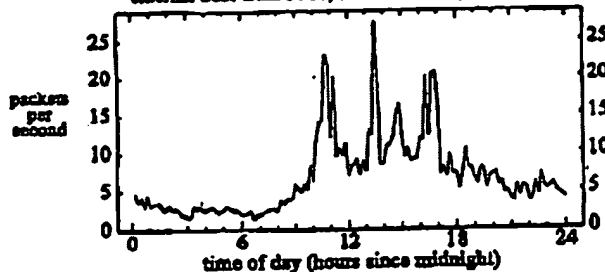
3. Characterization of Arrival Behavior

The LAN traffic monitor just described has been used to record data from several hundred million Ethernet packets on Ethernet cables accessible within Bellcore's Morris Research and Engineering Center during August 1989 through January 1990. In this section, we characterize the observed arrival behavior of the external traffic, with particular attention to the wide range of time domains made accessible by our high time-resolution, long-term data collection. The availability of this data allows a more careful consideration of the issue of "burstiness" than has previously been possible. For brevity, our examples are largely drawn from aggregate external traffic recorded during October, 1989; where appropriate, we will compare these results with other studies in the literature, with our observations from other months, with synthetic traffic models, and with measurements of internal traffic.

The external traffic represents essentially all Ethernet traffic between Bellcore corporate and laboratory hosts and all hosts outside of Bellcore on the Internet. During the year of our observations, this traffic was routed within Bellcore to a single T1 (1.544 Mbit/second) line that provided our external network access; the data below were gathered by monitoring the Ethernet directly supplying this external router and extracting records for all packets delivered to or originating from this router. At the time when we gathered our data, access between Bellcore hosts and the outside world was completely unrestricted; all Bellcore hosts could speak to any host accessible via the Internet.

The internal traffic data used in this study comes from a network serving a laboratory of about 120 people, most of whom had a Sun-3[®], Sun-4[®], or DECstation[®] 3100 workstation on their desk. It also serves nine file servers and a small number of high-end minicomputers, and is connected to the rest of Bellcore via a router.

Figure 3.1.1: Packet arrival rate vs time of day
external trace from 14:37, 10 Oct to 10:19, 11 Oct 1989



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3.1 Arrival Rates

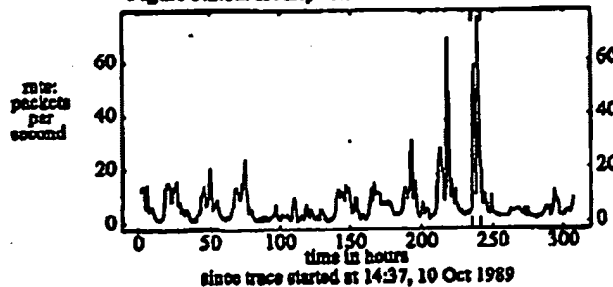
The most familiar characterizations of packet traffic are arrival rates over medium to long time scales: the number of bytes or packets seen per second, hour, or day. The classic 1979 study of a 2.94-megabit-per-second Ethernet by Shoch and Hupp^[1] reported seeing about 2.2 million packets per day, representing less than 1% utilization of the network capacity, with a pronounced diurnal cycle. The diurnal cycle is readily apparent in our current measurements of aggregate traffic, both for internal and external traffic (as illustrated for external traffic in Figure 3.1.1), but the value of "less than 1% utilization" is no longer realistic, even given the higher 10-megabyte per second Ethernet speeds now in use: for internal traffic, mean monthly utilization exceeded 15%, with daily peak hours generally exceeding 30% utilization on weekdays and peak minutes exceeding 50%. (Our internal Ethernets each carry about half as many packets as an average link in the current national Internet backbone^[10]; on the order of 30 million packets a day; it is interesting that this ratio was also true in Shoch and Hupp's study, despite the order of magnitude increase in absolute load over the past decade.)

The aggregate external traffic from all of Bellcore is typically 4% to 8% of the volume of traffic seen on a fairly heavily loaded internal Ethernet cable. Thus, the mean daily utilization of the Ethernet that can be attributed to external traffic is now in the 1% range characteristic of all internal traffic in 1979. The peak utilizations observed over shorter times for external traffic also closely match the 1979 internal traffic peaks: for example, the peak external minute in October, 1989, represented an Ethernet utilization of 14.7%, while Shoch and Hupp reported a peak minute of 16%. This comparison suggests that the burstiness characteristics described below may well have been true in 1979 as well as in our 1989 study; unfortunately, the analysis techniques described below are not available for the 1979 report. One should note, moreover, that peak utilizations for the external traffic are bounded by the 1.544-megabit per second external access line, which limits possible Ethernet occupancy by external traffic in our study to 15.4%; for periods as long as a few minutes, 95% of available external access is utilized.

3.2 "Burstiness"

For purposes of modeling the demand on network resources, the most critical feature of the arrival rates is that they are highly bursty over a very wide range of time scales. Figure 3.2.1a displays the mean packet arrival rates over each hour for a monitored period of 307 consecutive hours of external Ethernet traffic; when this figure is compared with the finer-scale display of the peak subinterval from this period (Figure 3.2.1b), which presents the arrival rates in successive one minute intervals in the busiest 6 hours from the 307-hour period, the gross similarity of the wildly varying arrival rates is striking. Informally, one can say that there is no natural length of a burst: at every time scale, closer examination shows that a "busy period" consists of a few "very busy" subperiods separated by comparatively "slow" intervals.

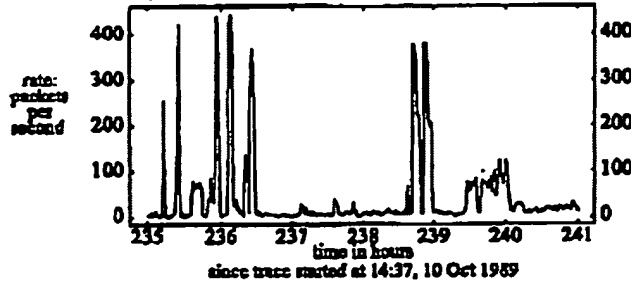
Figure 3.2.1a: Hourly arrival rates of external traffic



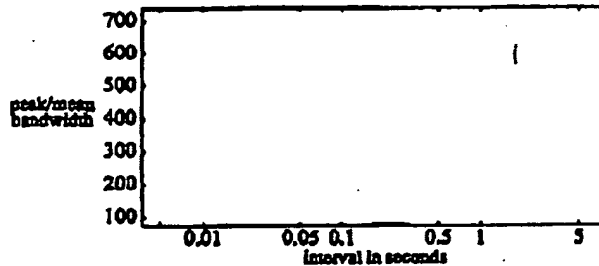
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Figure 3.2.1b: Arrival rates by minute, busiest 6 hours



This behavior in actual traffic creates difficulties for many conventional measures of "burstiness". Three commonly used definitions are the ratio of peak bandwidth to mean bandwidth, the coefficient of variation, and the index of dispersion. As Figure 3.2.2 illustrates, the observed value of peak bandwidth depends critically on the time interval over which the bandwidth is determined. For this particular two-week sample of external traffic, the peak rate in bytes per second observed in any 5 second interval is 152 times the mean arrival rate, while the peak rate observed in any 5 millisecond interval is 715 times the mean. The disparity in peak-to-mean ratios is even higher when packet arrival rates are calculated, spanning a ratio of 73 to 861 for 5-second to 5-millisecond intervals in this sample.

Figure 3.2.2: Peak to mean ratio for external traffic
external trace from 14:27, 10 Oct to 10:19, 23 Oct 1989

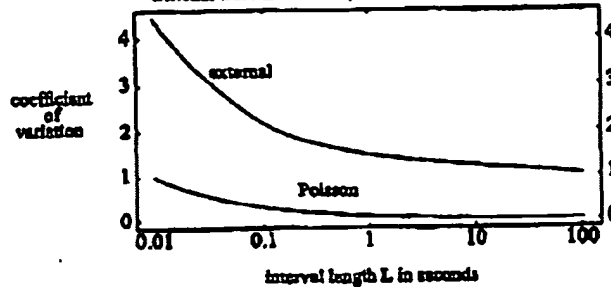
The coefficient of variation and the index of dispersion may be defined either for interarrival times or for arrivals^[11]. In the limiting case of extremely long measurement periods, the two definitions present the same information; here we shall concentrate on the arrival values. The coefficient of variation for arrivals in a given time interval of length L is the ratio of the standard deviation in the observed number of arrivals in a time interval of length L to the observed mean number of arrivals in that time interval. Figure 3.2.3 compares the observed coefficient of variation for arrivals for the external traffic of our running example with the coefficient of variation for a Poisson arrival process with a mean arrival rate of 100 packets per second. Intuitively, one may say that simple, analytically tractable models (such as a Poisson, batch Poisson, hyperexponential, or Markov-modulated Poisson process) have very little long-range variability: the coefficient of variation for arrivals rapidly converges to zero outside the characteristic time domain of the model. In sharp contrast, the observed traffic has burstiness at all time scales throughout the regime from milliseconds to thousands of seconds.

Recently, several researchers^{[12] [13] [14]} have proposed adapting formal models to observed "burstiness" behavior by employing the index of dispersion. This measure is closely related to the coefficient of variation, and is commonly used to explore the effects of different time scales on estimates of burstiness. For a given time interval of length L , the index of dispersion for arrivals^[11] over L is the variance in arrivals per interval of length L , divided by the mean number of arrivals in an interval of length L . Figure 3.2.4 shows the index of dispersion for both internal and external traffic over the month of October, 1989. It is particularly noteworthy that the index of dispersion shows extremely similar behavior for both internal and external traffic despite the great difference in their

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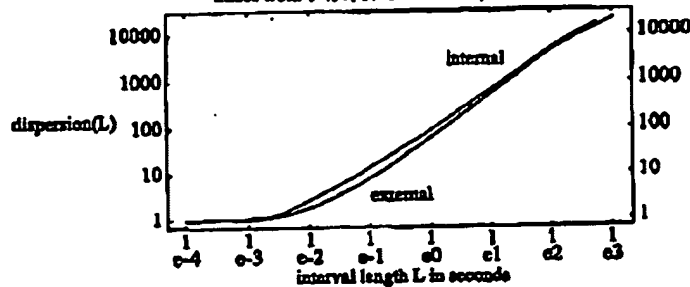
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Figure 3.2.3: Coefficient of variation (arrivals)
external trace from 14:37, 10 Oct to 10:19, 23 Oct 1989



absolute arrival rates, and that it monotonically increases throughout a time span of 6 orders of magnitude (although it does apparently converge to an upper bound when L is on the order of days). Figure 3.2.5 displays, for comparison, the indices of dispersion for 10 million packets generated by some simple formal models (Poisson, batch Poisson, and deterministic batch) fitted to the observed external traffic data. Pure Poisson processes always have an index of dispersion equal to one; the other simple models rapidly converge to small fixed values. Indeed, more complex models constructed from Poisson distributions, such as hyperexponential and MMPP (Markov-modulated Poisson process) arrival distributions, have indices of dispersion that converge to fixed values over a time scale on the order of the time constants of the models. The large range of monotonically increasing dispersion observed for actual traffic suggests that even fairly sophisticated MMPP models, such as those of Gusella^[12], Srinani and Whit^[13], or Hefkes and Lucantoni^[12], may not characterize the actual traffic behavior well over the range of significant time scales.

Figure 3.2.4: Index of dispersion (arrivals)
traces from 14:37, 10 Oct to 10:19, 23 Oct 1989

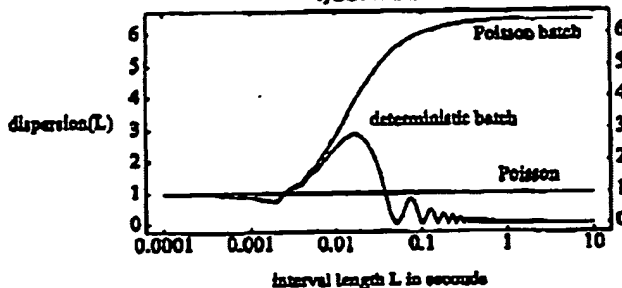


3.3 Inter-arrival Times

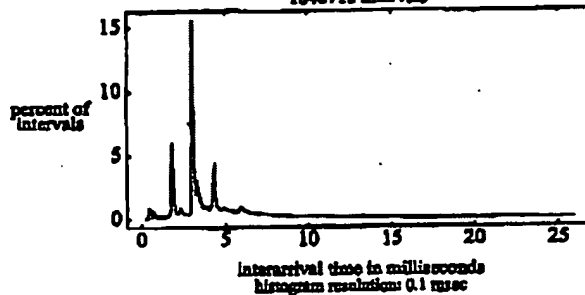
For many interactions between LANs and LAN-interconnection networks, the critical time constants are in the range of milliseconds to hundreds of milliseconds. Given the high precision of our packet timestamps, we can analyze packet arrival times to determine if the driving traffic load has significant structure in this time domain. Figure 3.3.1 shows the distribution of the time intervals between successive packet arrivals for long packets (containing from 200 to 800 bytes) from the 307-hour period of external Ethernet traffic shown above. For this extended sample, the distribution is sharply confined to a few specific inter-arrival values, reflecting particular protocol implementations' transmission and acknowledgement strategies. The peaks in the inter-arrival distribution become less well-defined as the traffic load increases, so that a memoryless (Poisson) arrival model may achieve an acceptable fit to the inter-arrival data for the busiest periods. This effect arises from the interleaving on the Ethernet of traffic generated by many independent applications, but does not imply that time-correlations can be ignored in modeling interconnect behavior under heavy load. These practical problems require models that capture the underlying correlations across time: actual applications create sequences of time-correlated packets, such as request-response pairs and higher-level protocol data units. Establishing the high time-resolution traffic correlations

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Figure 3.2.5: Index of dispersion (arrivals)
synthetic traffic

caused by such sequences of related packets (or "packet trains") cannot be done by studying inter-arrival distributions alone, nor by analysis techniques designed for interpreting truly periodic events. For example, the point-process power spectrum for the same data shows only one significant peak below 100 milliseconds: a small peak at 10 milliseconds, apparently caused by host system timers.

Figure 3.3.1: Distribution of Ethernet interarrivals
external trace from 14:37, 10 Oct to 10:19, 23 Oct 1989
1848718 intervals

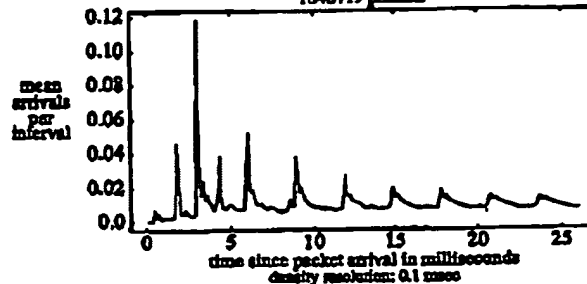
3.4 Palm Distributions

The inadequacies of these techniques for capturing the short-term time correlations of arrivals suggest the use of a measure that is sensitive to short sequences of time-correlated packets. One such statistical measure is the *Palm distribution*, a form of pairwise interpacket time histogram. Formally, the Palm distribution $P(L)$ is the expected number of arrivals within the time interval T to $T+L$, conditional on an arrival at time T . Let the consecutive arrival times be a_1, a_2, \dots and let $N(T_1, T_2]$ be the number of arrivals in the time interval $(T_1, T_2]$. Then $P(L) = E(N(T, T+L] | T = a_i \text{ for some } i)$. The Palm density for an interval $(L_1, L_2]$ is defined as $P(L_2) - P(L_1)$. Figure 3.4.1 displays the Palm density function for the same traffic sample used in section 3.3. Two aspects of short time scale application behavior are readily apparent from this perspective: the high peak for pairs separated by a very few milliseconds (reflecting both short trains and rapid responses), and the gradually decaying peaks extending out for many packet times (reflecting, among other issues, the presence of longer but imprecisely-defined packet trains). The well-defined separation between successive peaks in the Palm distribution can be explained in terms of sequences of packets being sent as rapidly as possible, constrained by the time required to transmit packets of these lengths over the Ethernet and the external internet and by the buffering and windowing behavior of the TCP protocol implementations that are responsible for most external packet traffic. The gradual widening of each peak graphically illustrates the effects of variations in roundtrip times on protocol acknowledgements and subsequent packet transmissions; the onset of each peak (which is limited by the minimal possible times for sending successive packets) is more sharply defined than the trailing edge (which is spread out by statistical variations). The implied broadening in the spacing of packets within a packet train suggests why spectral analysis reveals little about high time-resolution behavior.

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Figure 3.4.1: Palm density of Ethernet arrivals
external trace from 14:37, 10 Oct to 10:19, 23 Oct 1989
1848719 packets



4. Effects of Actual LAN Traffic on LAN Interconnections

The short-range correlations in measured LAN traffic, as illustrated in the previous section, significantly affect the loss and delay characteristics that will be seen when external LAN traffic is submitted to the access points of proposed wide-area LAN interconnection services. This section illustrates some effects of traffic burstiness on the loss and delay behavior imposed by one proposal for traffic shaping (buffering and rate limitations) at this interconnection access point.

We shall take as our example the access class scheme proposed for SMDS service^[10] on public B-ISDN networks. This proposed service appears well-suited for providing wide-area interconnection of LANs, provided that significant levels of statistical multiplexing can be achieved with acceptable delay and loss behavior. SMDS service is envisioned as offering connectionless packet delivery, through interfaces that split variable length packets into fixed-size cells (level 2 protocol data units) and reassemble the packets at the egress point. Although the detailed structure of the cells is largely immaterial to the clients (such as LANs) using this service, the traffic shaping imposed by the network interface is significant. Packets arriving from a LAN are buffered at the interface and delivered to the B-ISDN network as cells at some maximum rate, subject to traffic shaping that limits the burstiness and the sustained input rate. Packets that do not entirely fit within currently available buffer space are dropped, so that partial packets are not transmitted. A wide variety of service classes are possible under SMDS service; because our external traffic was collected from a network utilizing a T1 (1.544 Mbits/second) connection for external access, this section explores the effects of submitting this traffic to the lowest rate (DS1-based) SMDS service access path. At this level of service, the maximum effective throughput available to the client is 1.173 Mbits/second.

The amount of buffering provided at the interface strongly affects the total packet delay and loss observed by the LAN. For this access path, the proposed SMDS service requirement is for less than 0.01% of the packets to be lost and for 95 percent of the packets to be delivered with less than 140 milliseconds delay. Simple analytical models based on our observed external traffic suggest that these requirements can be readily met. The relationship seen between delay and loss, however, is extremely sensitive to burstiness in the traffic. To observe the effect of actual traffic, the authors wrote a trace-driven discrete-event simulation that models the behavior of the SMDS service interface buffer for synthetic and actual traffic. In the figures below, the curves labeled "external" represent simulation results derived using the entire 307-hour external traffic trace of previous sections; the curves labeled "Poisson" and "batch Poisson" represent, respectively, a pure Poisson arrival process of 192-byte packets (the mean length of the observed external traffic packets) and a batch Poisson process with fixed-length batches of 8 1024-byte packets arriving deterministically within each batch at 2-millisecond intervals (imitating packet-train characteristics suggested by the Palm distribution seen in Figure 3.4.1).

The selection of appropriate arrival rate parameters for the formal models is especially problematic, as directly matching the observed arrival rates of external traffic yields simulated losses of less than 10^{-7} , with negligible delay: 95% of packets having no buffering delays at the interface, and 99.9% having less than 13.6 milliseconds delay. For the plotted figures, the parameters for the two traffic models have been chosen so that the resulting mean packet loss rate matches the mean packet loss rate obtained for external traffic when the interface buffer capacity is 209 cells (approximately 70 milliseconds maximum delay). For the Poisson arrival process, this selection criterion

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required an arrival rate of 655 packets per second, while for the batch Poisson process the criterion required a mean arrival rate of 0.4 batches (3.2 packets) per second. The disparity between the mean rates required to match the loss rate for realistic traffic and the observed mean external rate of 6.74 packets per second is striking. As Figures 4.1.1 and 4.1.2 illustrate, even the expedient of selecting model parameters to mimic the loss behavior at one buffer size for the observed traffic results in extreme departures between simulations based on modeled and observed traffic at other buffer dimensions.

Figure 4.1.1: Buffer size vs packet loss
transmission rate: 1.173 Mbit/sec

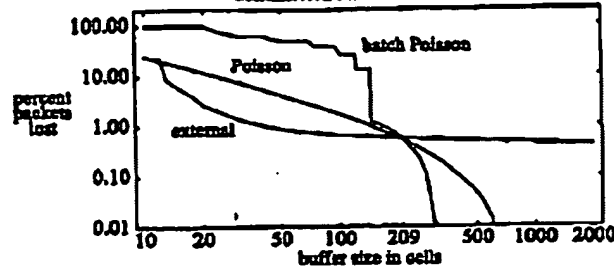
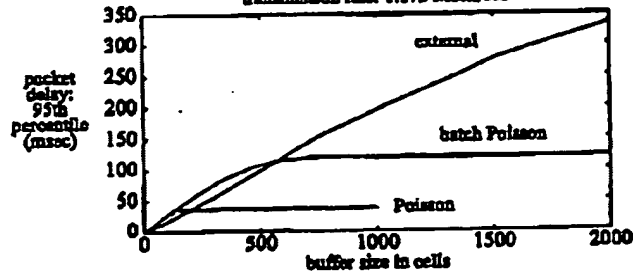


Figure 4.1.2: Buffer size vs packet delay
transmission rate: 1.173 Mbit/sec



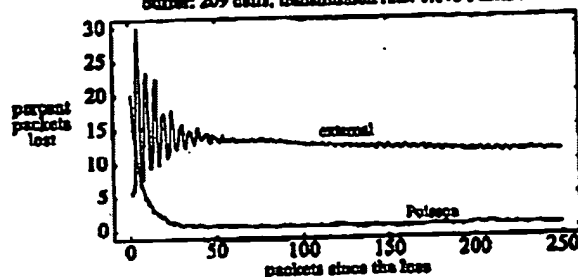
Both loss and delay behaviors differ qualitatively between simulations based on actual traffic and those based on these formal models: mean packet loss decreases very slowly with increasing buffer capacity, in sharp contrast to the Poisson-based models where losses decrease exponentially with increasing buffer capacity; packet delay always increases with buffer capacity, in contrast to the models where delay does not exceed a fixed limit regardless of buffer capacity. The distinctive loss and delay patterns seen with observed traffic stem from the wide range of time scales over which the traffic is bursty: losses occur when short time-frame "bursts" occur during longer time-frame "swells", so that if a packet is dropped, following packets are likely to be dropped for a long time thereafter. This effect can be seen in Figure 4.1.3, which shows the conditional probability of subsequent packets being dropped immediately following the loss of one packet. Looking at longer time scales, one observes that the conditional loss probabilities for Poisson traffic rapidly revert to the mean packet loss rate of 0.5%, while loss probabilities based on actual traffic remain more than an order of magnitude above the mean loss rate for hundreds of subsequent packets. At short time scales, the pronounced short-term correlations in the observed traffic create complex oscillatory loss behavior.

These results emphasize the importance of burstiness in aggregate LAN traffic, and the influence of the wide range of time domains over which burstiness occurs. Nonetheless, these preliminary trace-based studies are subject to inherent limitations. Most seriously, trace-based simulations do not accommodate the response of flow-controlled application protocols to the delays and losses induced by longer time-domain burstiness. Over times comparable to multiple roundtrips through the interconnected networks, adaptive higher-level protocols can significantly reduce their loss rates. At the shortest time scales considered here, however, client-level protocols cannot react in time to avoid the patterns of loss and delay suggested by trace-driven studies. Despite the shortcomings of simulations

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Figure 4.1.3: Conditional losses
 buffer: 209 cells; transmission rate: 1.173 Mbits/sec



based on recorded traffic, it is clear that future studies of LAN interconnection networks and their congestion management mechanisms must consider traffic that is extremely bursty over an extremely wide range of time scales.

5. Summary

We have implemented and tested an Ethernet traffic monitor that correctly captures all packets in the observed networks, with timestamps accurate to better than 100 microseconds. The availability of this unique high-quality data in turn permits the consideration of the behavior of aggregate LAN traffic across a wide range of time scales, and the use of analysis tools suited to these time scales. Brief examples are presented here of the results revealed by peak-to-mean ratios, indices of dispersion, inter-arrival time distributions, and Palm densities; these observations suggest that busyness is severe across a far wider range of time scales than is easily captured by conventional formal traffic models, while the critical short-range correlations have substantial internal structure that profoundly affects loss and delay behavior. Despite the great disparity in absolute arrival rates seen in internal and external traffic, the structure revealed by their indices of dispersion and Palm densities is surprisingly consistent. More generally, although this paper has largely restricted its examples to a single month of external traffic, the extremely bursty behavior seen here is not idiosyncratic: measurements taken on various Ethernet cables within the company (with quite different user populations and gross traffic rates) show similar results, as do measurements taken from March 1989 through January 1990.

The appearance of burstiness across so extensive a domain of time scales is not merely significant for the design of better models of LAN traffic, but crucial for correctly modeling the behavior of traffic under conditions of congestion. The measurement, analysis, and understanding of the high time-resolution behavior of aggregate LAN traffic provides a valuable resource for designing LAN interconnection schemes and for anticipating the patterns of loss and delay these schemes may impose on their client LANs.

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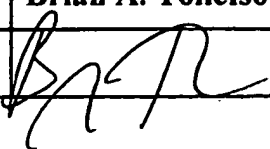
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